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HYPERSONIC RESEARCH PROJECT

Memorandum No. 34

October 1, 1956

THE EFFECT OF A SIMPLE THROAT DISTORTION ON THE DOWNSTREAM FLOW IN A HYPERSONIC WIND TUNNEL NOZZLE

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ARMY ORDNANCE CONTRACT NO. DA-04-495-Ord-19

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ABSTRACT

An experimental investigation was conducted in the GALCIT 2½" Supersonic Wind Tunnel to determine the effect of a known distortion of the throat section of a hypersonic nozzle on the flow in the region downstream from the throat. The flow in the nozzle with a rectangular throat section was compared with the flow in the same nozzle with the throat region distorted to produce a throat height which varied linearly across the throat section. The flow was investigated by means of Pitot pressure surveys in the horizontal plane of symmetry of the undistorted nozzle.

The magnitude of the effect produced by the throat distortion was observed to be approximately that predicted by one-dimensional isentropic flow relations. However, the sign of the effect was reversed in about the distance required for a curved Mach line to cross the channel.

I. INTRODUCTION

Hypersonic wind tunnel nozzles are designed to operate at stagnation temperatures sufficiently high to prevent condensation of air in the test region. The required stagnation temperature T_o increases rapidly with increasing test section Mach number M_t. For example, for a test section Mach number of 6 and a reservoir pressure of 100 psia, the stagnation temperature must be at least 300°F, while for a test section Mach number of 9 and a reservoir pressure of 500 psia, the stagnation temperature must be at least 1050°F. For high Mach number nozzles the high heat transfer rates in the throat region can obviously produce large thermal expansions or distortions of the nozzle material unless this region is either cooled or is made from a material with low thermal expansion properties. Either method of avoiding thermal distortions in the throat region presents a difficult design problem. The amount of throat distortion which can be tolerated is, then, of prime importance to the designer of hypersonic wind tunnel nozzles.

This investigation was undertaken to provide some quantitative information about the effect of a known throat distortion on the flow properties in the region downstream from the throat. The scope of the investigation was to determine the streamwise distance-history of the effect of distortion in the region downstream from the throat.

The nozzle and test section used in this investigation were designed and built by the Jet Propulsion Laboratory staff. The distorted throat configuration was proposed by Dr. Joseph Sternberg of the

Ballistic Research Laboratory, Aberdeen Proving Grounds, Maryland. The authors wish to express their appreciation for the many helpful suggestions and the guidance provided by Dr. C. B. Millikan, Professor L. Lees, and Mr. Toshi Kubota of GALCIT and Dr. P. Wegener of JPL.

II. EXPERIMENTAL EQUIPMENT AND PROCEDURE

A. Description of the Wind Tunnel

The experimental investigation was carried out in the GALCIT $2\frac{1}{2}$ by 3 inch Supersonic Wind Tunnel. This facility is described in Reference 1. Both the Supersonic Wind Tunnel compressor plant and the Hypersonic Wind Tunnel compressor plant were used in a parallel arrangement to operate the wind tunnel.

B. Description of the Test Section

A sketch of the test section configuration is shown in Figure 1. This test section is the same as was used in the investigation of Reference 1. Figure 3 shows the nozzle contour and the location of static pressure orifices. The undistorted throat cross section was 2.6 inches wide and nominally 0.084 inch high. The distorted throat cross section was 2.6 inches wide with the height varying linearly from 0.084 inch to 0.088 inch. The method of producing the distorted nozzle shape is shown in Figure 4. Figure 5 shows the measured throat cross sections both before and after the distortion.

C. Instrumentation

Instrumentation included a model support system with an axial drive mechanism, a nine-tube Pitot pressure rake, a multiple tube mercury manometer with a vacuum reference, a carbon dioxide cooled dew point indicator, a mercury-in-glass thermometer for reading the stagnation temperature, and a Tate-Emery indicator for measuring the reservoir pressure.

The Pitot pressure rake (Figure 2) was made from 0.032 inch O.D. stainless steel tubing. The rake was mounted in the test section so that the center tube remained on the test section axis throughout the horizontal traversing. The other tubes were spaced 0.25 inch apart in the horizontal plane through the tunnel axis.

D. Test Procedure

Transverse Pitot pressure profiles were obtained from the nine tube rake at several axial stations between $2\frac{1}{2}$ and $11\frac{1}{2}$ inches downstream from the throat. These profiles were obtained first for the undistorted throat. The lower nozzle block was then removed without disturbing the rake mounting. Material was removed by hand from the throat region of this block as indicated in Figure 4. The block was mounted in its original position in the test section, and transverse Pitot pressure profiles were then obtained for the distorted nozzle at the same axial stations as for the undistorted nozzle described above.

Before each test the actual throat height was measured at several transverse positions by pulling lead wires through the throat. This was done after the side plates had been fastened securely in position, and care was taken not to disturb the nozzle block positioning after this measurement was made. The results of these measurements are shown in Figure 5.

Static pressures on the centerline of the upper nozzle block were measured at the beginning of each test run with the total head rake in its most rearward position. Two static pressure orifices in the north sideplate at the same axial position and equally spaced above and below the horizontal plane of symmetry were used to indicate symmetry of flow conditions during each run.

All test runs were made at a stagnation pressure of 50 psig, stagnation temperatures between 70 and 90 degrees Fahrenheit, and dew points of the reservoir air near -30 degrees Fahrenheit measured at atmospheric pressure.

III. DISCUSSION OF RESULTS

The results of the Pitot pressure measurements are shown in Figures 6 and 7 for the undistorted and distorted throat regions respectively. The general shapes of the profiles are similar in both figures; however, the profiles of Figure 7 appear to be rotated about a point near the centerline as compared to those of Figure 6 for all profiles downstream from X = 2.86 inches. A remarkable feature of the distorted throat Pitot pressure profiles is that they indicate higher Mach numbers downstream from the wider portions of the throat, for all profiles downstream from X = 2.86 inches.

The cause of the waviness of the profiles of Figures 6 and 7 is unknown; however, since the same profile shapes remained after the distortion machining, it is assumed that the cause does not lie in the immediate vicinity of the throat. One possible cause is slight leakage around the static pressure orifices in the upper nozzle block. Inaccessibility of the tubes leading to these orifices prevented positive sealing measures.

In order to show the gross effects of the throat distortion without the effects of the extraneous disturbances, the data points of Figures 6 and 7 were replotted as curves of p_o'/p_o versus X for each of the nine Pitot pressure tubes. Smooth curves were then faired through these points. The constant Mach number contours of Figures 8 and 9 were derived from these faired curves. The fairing removed much of the effect of the apparently random waviness in the Pitot pressure profiles. The effect due to the throat distortion is obvious in the slopes of the Mach number contours of Figure 9 in contrast to the nearly zero-slope contours of Figure 8.

The magnitude of the effect of the throat distortion is approximately that predicted by one-dimensional isentropic relations. The approximate axial distortion of the Mach number contours as predicted by one-dimensional theory is indicated on Figure 9 for several stations. Note that only the magnitude of the distortion is approximately the one-dimensional value, while the slopes of the contours are reversed.

In attempting to understand the reversal of the pressure profiles, the linearized supersonic wave equation (Reference 2) was applied to the flow in the plane of symmetry with the Mach number distribution as given by one-dimensional theory (Figure 3). Some of the resultant characteristics (Mach lines) are shown in Figure 10. The scale used in plotting Figure 10 is the same as that used for Figures 8 and 9 in order to facilitate correlation. With such a symmetrical system of Mach lines, one would expect that a pressure profile at any station would be reversed (and possibly distorted) in the distance required for a Mach line to cross the width of the channel. If Figures 9 and 10 are compared, it is seen that this is approximately the case. After the first reversal (in the neighborhood of X = 4 inches), the Mach lines are quite steep, and are becoming steeper (approaching the flow direction) so that the next reversal of the profile would not occur within the region of this investigation.

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2. Shapiro, A. H.: "The Dynamics and Thermodynamics of Compressible Fluid Flow", Vol. I, The Ronald Press Company, New York, 1953.

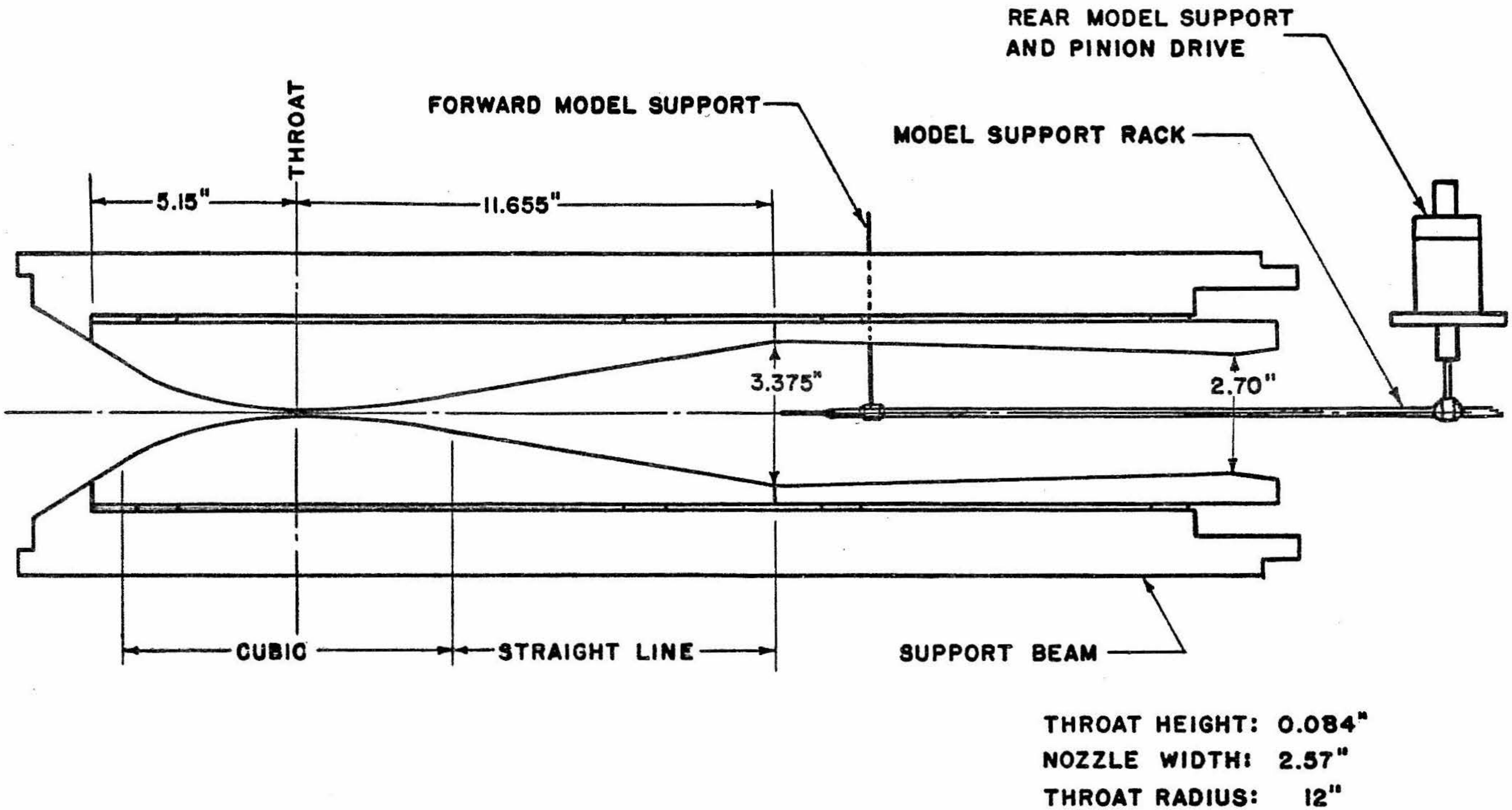
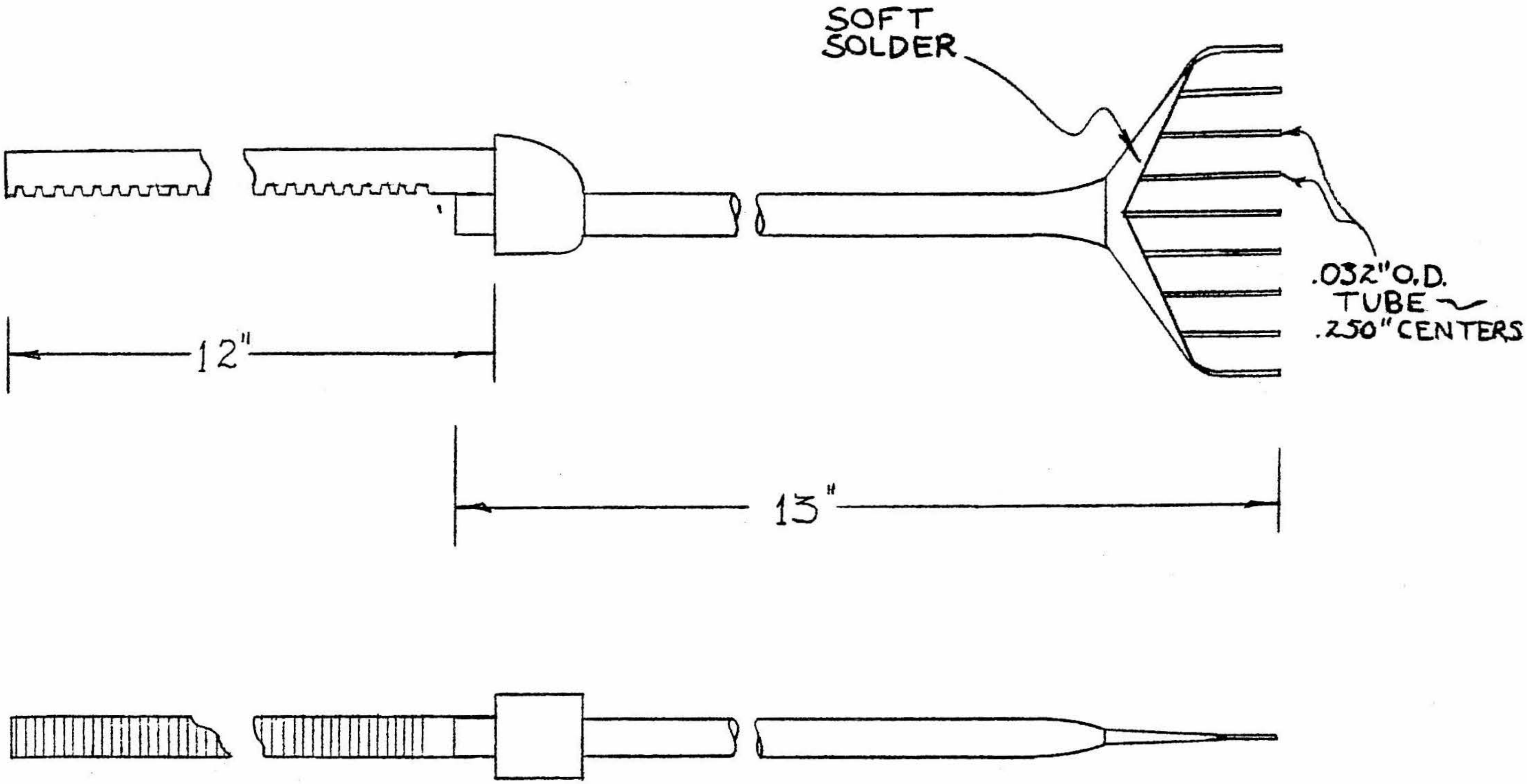


FIG. 1

TEST SECTION CONFIGURATION



PITOT PRESSURE RAKE

FIG. 2

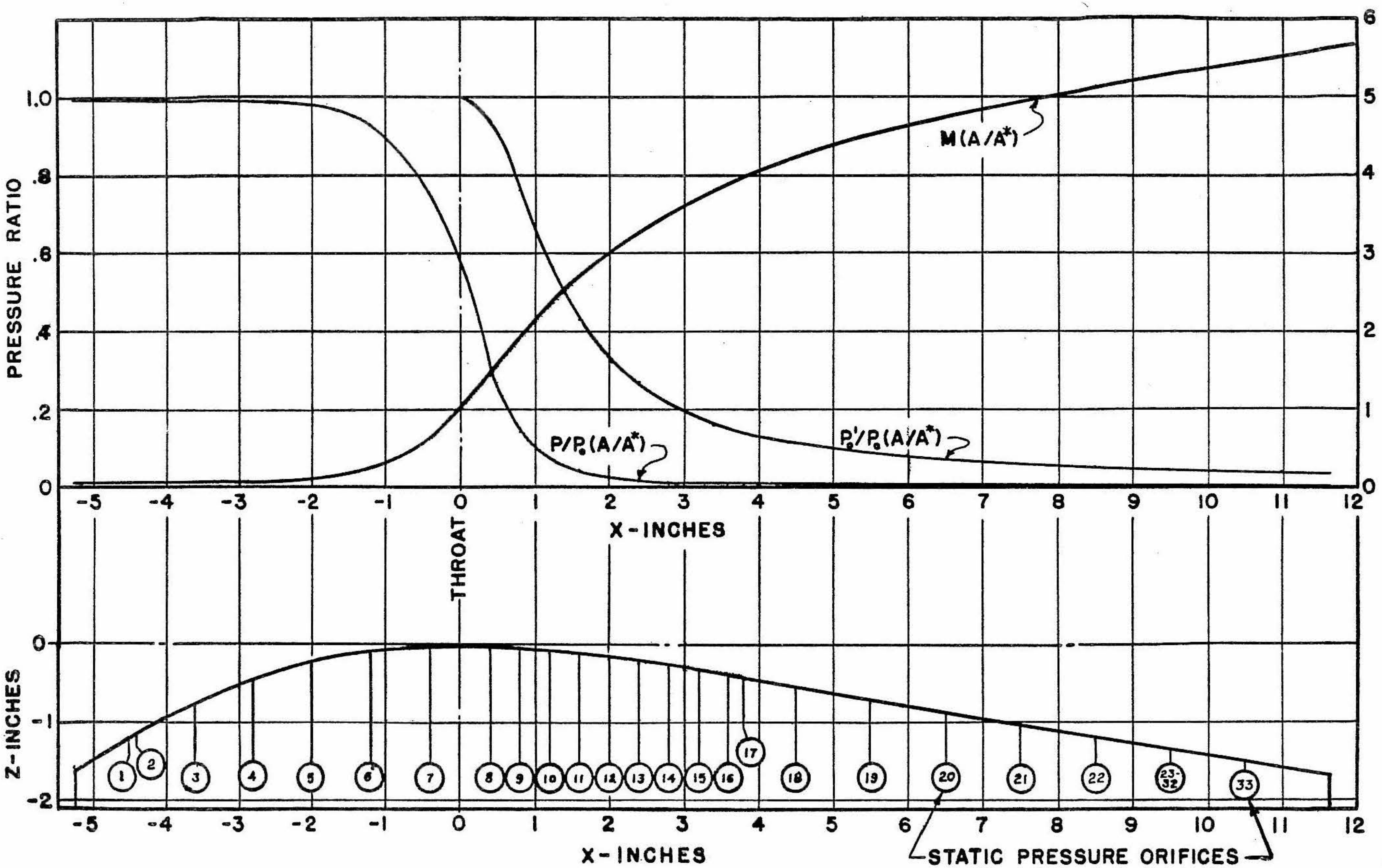
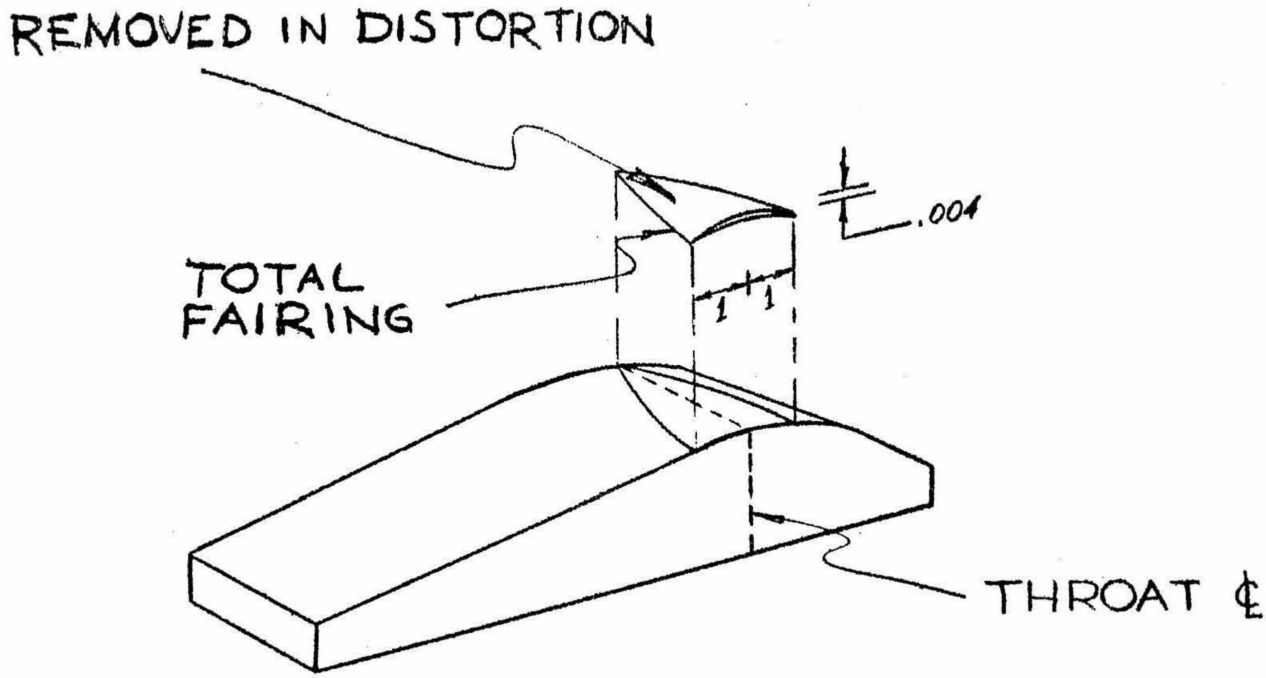
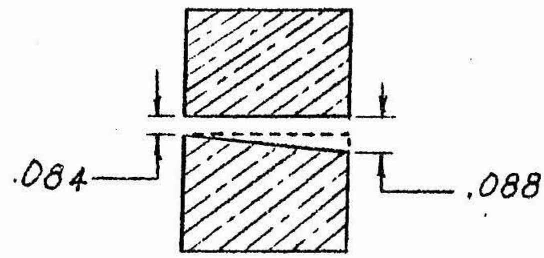


FIG. 3

ISENTROPIC NOZZLE RELATIONS





SECTION AT THROAT
LOOKING
UP STREAM

NOZZLE
DISTORTION
FIG 4

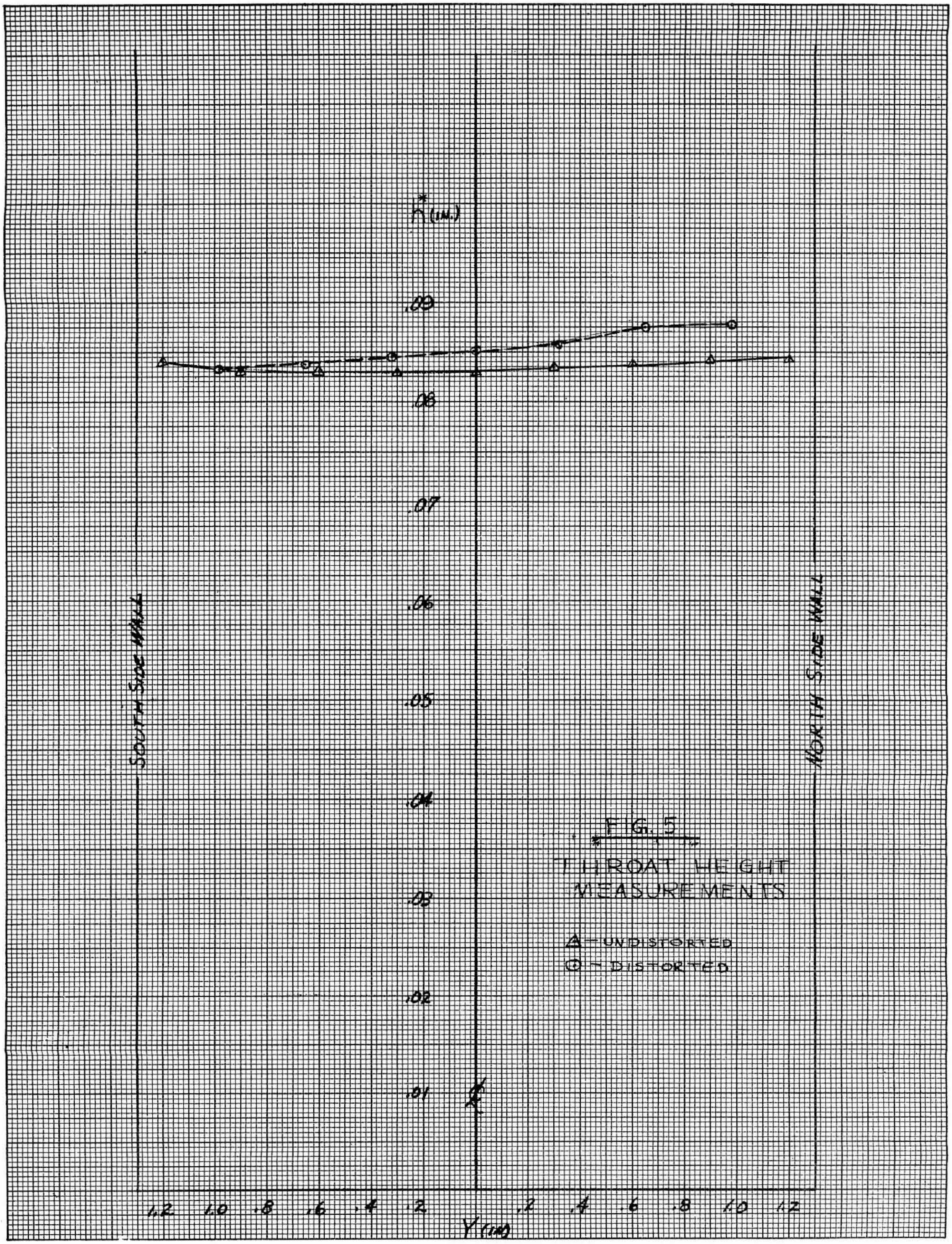
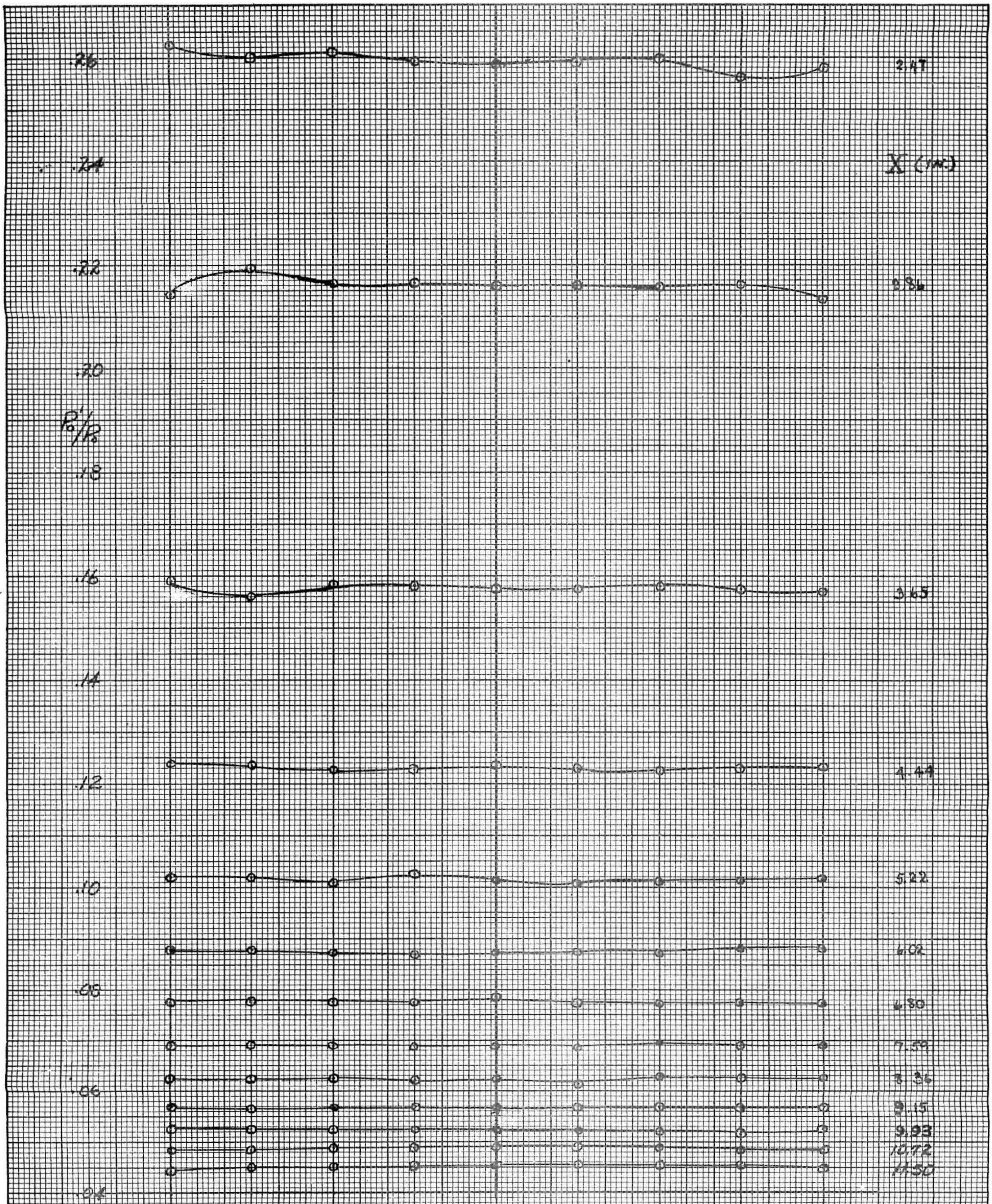


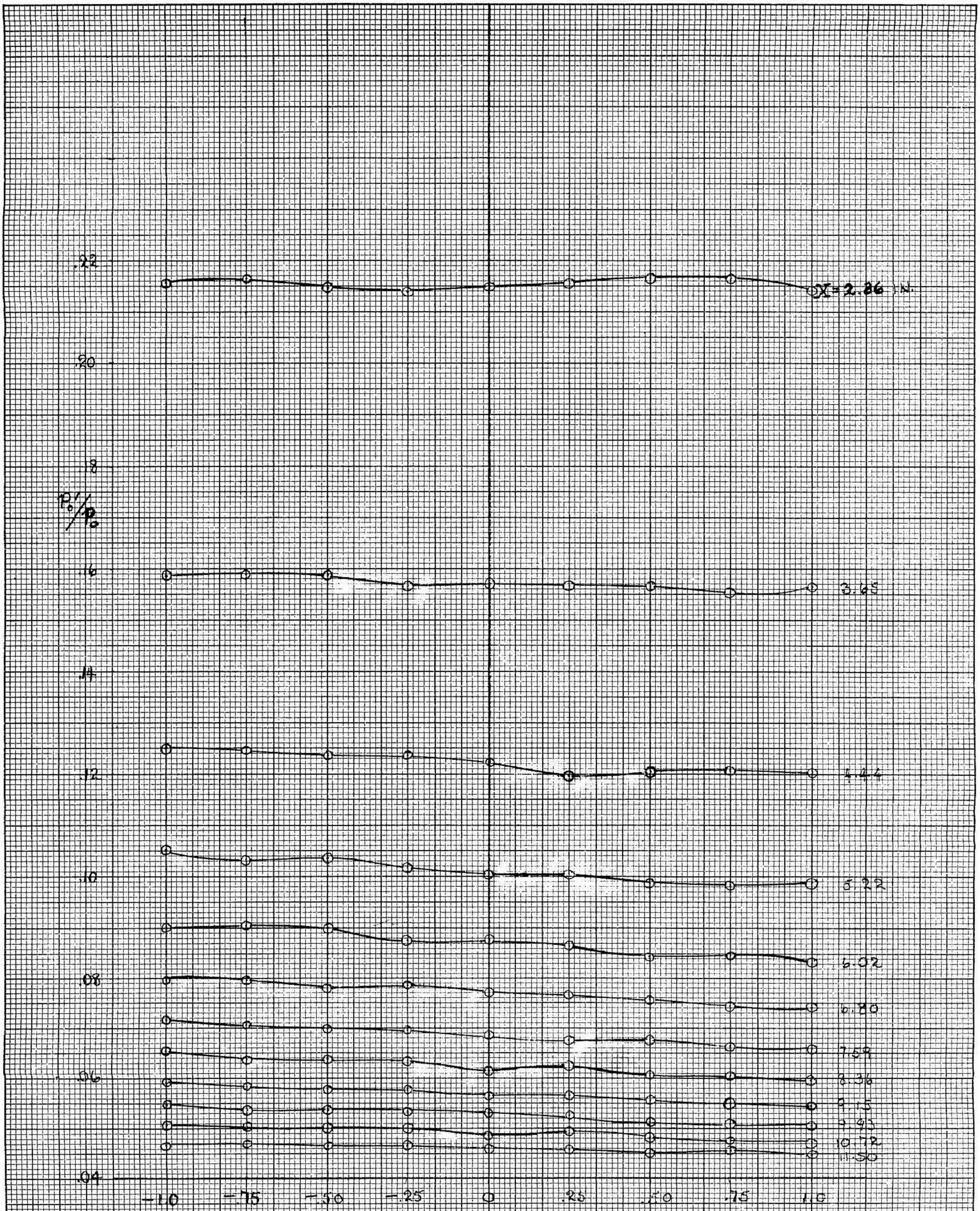
FIG. 5

THROAT HEIGHT MEASUREMENTS



PITOT PRESSURE PROFILES (UNDISTORTED THROAT)

FIG. 6



PITOT PRESSURE PROFILES (DISTORTED THROAT)

FIG. 7

ISOMACHS

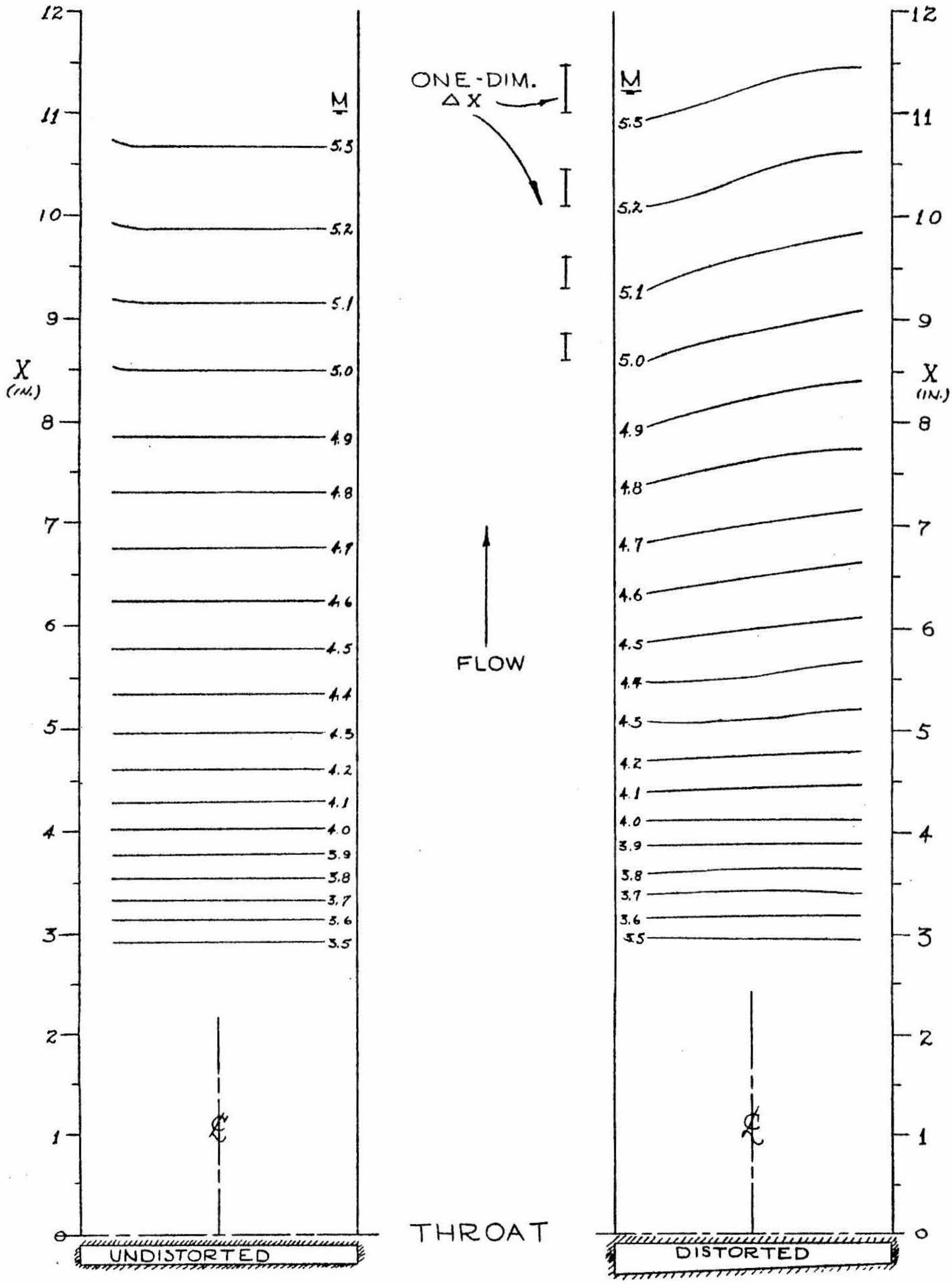


FIG. 8

FIG. 9

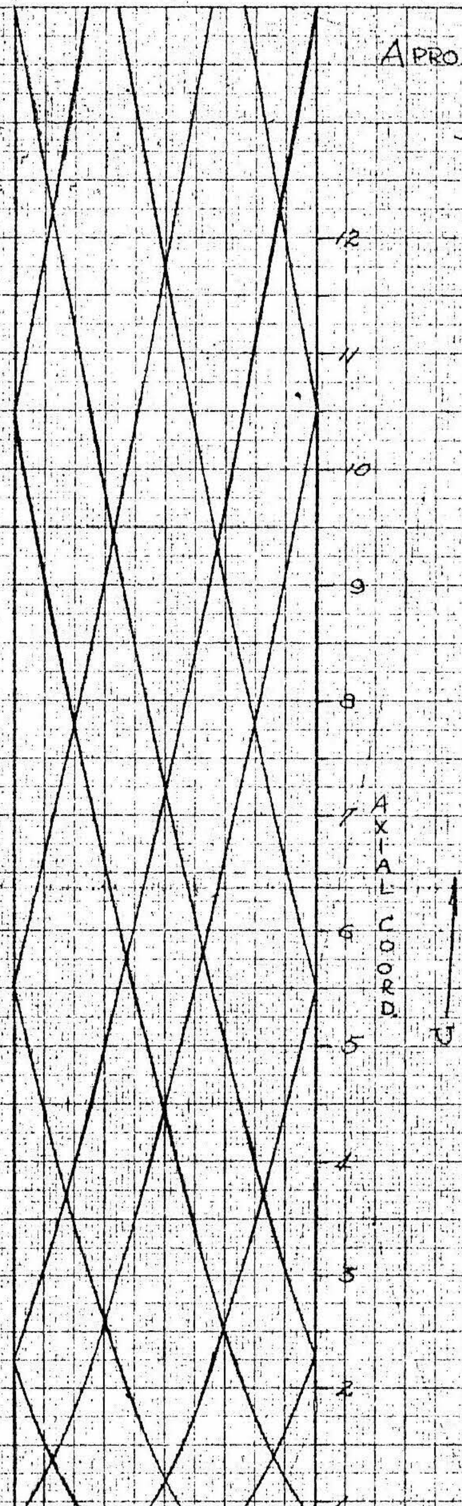
CONSTANT MACH NUMBER CONTOURS

APROX. 2-DIM. CHARACTERISTICS

$$\int \frac{dy}{dx}\,dx = \int \frac{1}{\sqrt{M^2(x)-1}}\,dx$$

FOR JPL-HWT-SWT
DISTORTED NOZZLE
INVESTIGATION

FIG. 10



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